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The effect of thermal inertia on office workers subjective and physiological responses; and performance under summer conditions

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Abstract

The objective of this study is to analyze the effect of different temperature ramps on office workers' psychological, physiological and behavioral reactions. This paper presents the analysis of the psychological and physiological reactions. The hypothesis is that a steeper ramp leads to more pronounced and earlier reactions. An experimental study in an outdoor facing climate chamber with two fully equipped office spaces was conducted. The results support the hypothesis stated at the beginning, but further in depth analyses especially together with the behavioral reactions need to be done before drawing conclusions for the applicability of light-weight structures.

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Keywords: Thermal comfort, physiological reaction, experimental study, performance, thermal inertia, work environment, summer

1. Introduction

Light-weight structures are getting more and more popular among architects and engineers due to their apparent design feature and flexibility. Previous studies have shown however that a high thermal inertia not only reduces the cooling load [1], but also improves thermal comfort conditions through the reduction of the rate of temperature fluctuations and an increased time-lag between outdoor and indoor conditions [2]. [3] and [4] assessed thermally comfortable conditions by a comparison of operative temperatures before and after the application of thermal inertia. Subjective comfort votes were not obtained.

Subjective comfort votes related to the rate of fluctuations were obtained in laboratory studies within artificial environments. Thermal acceptability at the same temperature was generally higher at steeper ramps [5]. Ramps of

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.5K/hr or less were concluded not to be distinguishable from constant environments [6]. [7] recommend the avoidance of ramps with slopes equal or above 4.4K/hr. Other studies did not find a significant difference [8].

However, it remains open, to what degree people are affected by the rate of change or the absolute temperature in real world environments and whether their way of interacting with the thermal environment differs according to the rate of temperature fluctuation.

The objective of this study is to analyze the effect of differently ascending temperature ramps on psychological, physiological and behavioral reaction. This paper presents the analysis of the psychological and physiological reactions. The hypothesis is that a steeper ramp leads to more pronounced and earlier reactions.

2. Methodology

For this study an experimental design with repeated measures was chosen, which took place in the climate chamber LOBSTER (Laboratory for Occupant Behavior, Satisfaction, Thermal comfort and Environmental Research) in Karlsruhe, Germany. Two identical fully equipped office rooms have one façade each to the outdoor environment. The windows can be opened and tilted. The tilting can be done mechanically either by pressing a button on the window catch or through the building control system. Five of six surfaces (all except the post and beam façade) are activated with a capillary tube system, which allows changing the set point temperature of each wall surface individually. In addition, each office is equipped with two underfloor convectors for supply and exhaust air with cooling and heating capabilities.

Subjects were asked to work for four half-day lasting sessions in the offices. With a few exceptions, two sessions were conducted within one day. The set point temperatures for indoor air and surface temperatures followed a pre-set protocol. The sessions differed in the starting temperature and ramp gradient as shown in Table 1. The order of sessions was randomized.

Subjects were allowed to tilt the windows, use the sun protection device, the ceiling fan, and the artificial lighting via a web-interface, i.e. with a mouse click. They had no control over the indoor air and surface temperatures – in fact, they were not told that such panel exists. The ramp gradient further depended on window and sun protection state chosen by the subjects (see Table 2).

Table 1. Session types, their starting temperature and ramp gradient.

Session	Starting temperature [°C]	Ramp gradient [K/hr]
W1	23.6	0
W2	23.6	0.8
W3	23.6	1.6
W4	26.0	0.8

Table 2. Adjustments to ramp gradient according to the state of window and sun protection device.

		Window		
		Closed	Open and Tin > Tout	Open and Tin < Tout
Sun protection device	Open	+/- 0 K/hour	-0.3 K/hour	+0.3 K/hour
	Closed	-0.3 K/hour	-0.3 K/hour	+/- 0 K/hour

During each session, subjects had to fill out a computer-based 5-minute comfort questionnaire with 30 items three times (see Fig. 1). The questionnaire was used to assess among others the thermal sensation vote (ASHRAE 7-scale), thermal preference (4-scale), thermal comfort (4-scale), perceived control (7-point scale), subjective productivity (7-point scale), and overall satisfaction (5-point scale).

At the end of each session (see Fig. 1), the subjects were prompted to conduct a 15-minute test-battery including three computer based performance tests: the Tsai-Partington test [9] with two screens with 25 randomly distributed numbers from 1 to 99 and 40 seconds time for each screen, a 5-minute lasting addition task [10] and an adopted version of the d2 test for the assessment of selective attention and concentration [11]. For this paper, the Tsai-Partington-test was analyzed by calculating the total number of correct links for both sheets, i.e. within 80 seconds.

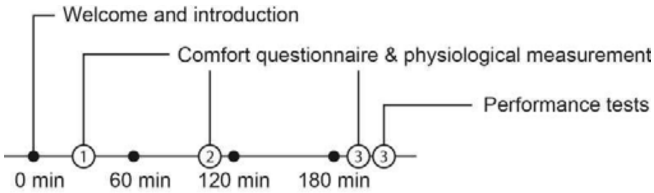

Fig. 1. Timeline of questionnaires and physiological measurements.

Physical and physiological (e.g. heart rate and skin temperatures) data was collected together with the subjects' interactions with windows, sun protection device, ceiling fan, and artificial lighting. The operative temperature was derived based on air temperature, globe temperature and air velocity measured adjacent to the workplaces close to the middle of the room. The neutral temperature was calculated using the Griffiths' method [12] and the regression coefficient derived from the linear regression of TSV on operative temperature for this dataset as described by [13]. From the heart rate data, the RMSSD as a measure of the stress level was calculated according to the function given in [14].

In order to reveal differences between the conditions, the Wilcoxon signed rank test for related samples [15] was performed throughout this paper using the statistical software R. The significance level was set to .05. As input to the test, the means of each measurement for each session type (experimental day) were calculated for each subject.

3. Results

In total 31 subjects (16 female) participated in this study of which one female subject could not complete all four conditions. The randomization could not be realized perfectly as shown in Table 3 due to organizational reasons. This is mainly because condition W4 was found to be mandatory in the afternoon.

Table 3. Times each session was conducted either in the morning or afternoon, first, second, third, or fourth.

Condition	Morning	Afternoon	First	Second	Third	Fourth	Total
W1	19(+1)	11	10(+1)	5	9	6	31
W2	22	8	12	6	9	3	30
W3	18	12	8	5	11	6	30
W4	1	29(+1)	0	14(+1)	1	15	31

The observed operative temperatures followed in the mean the preset protocol (Fig. 2a). During the times of measurements (Fig. 2b), the range of operative temperatures was 2 to 5K. This can partly explained by the variations in behavioral patterns. For the following, a focus will be set on the comparison between the third vote of condition W3 with the third vote of W4 (denoted as W3/3_W4/3) as well as between the third vote of W2 with the second vote of W3 (denoted as W2/3_W3/2). In both cases, the measurement with the less steep ramp gradient is having a significant higher operative temperature (W3/3_W4/3: mean 27.3°C vs. 28.2°C; p=.001 and W2/3_W3/2: mean 26.8°C vs. 25.8°C; p=.002).

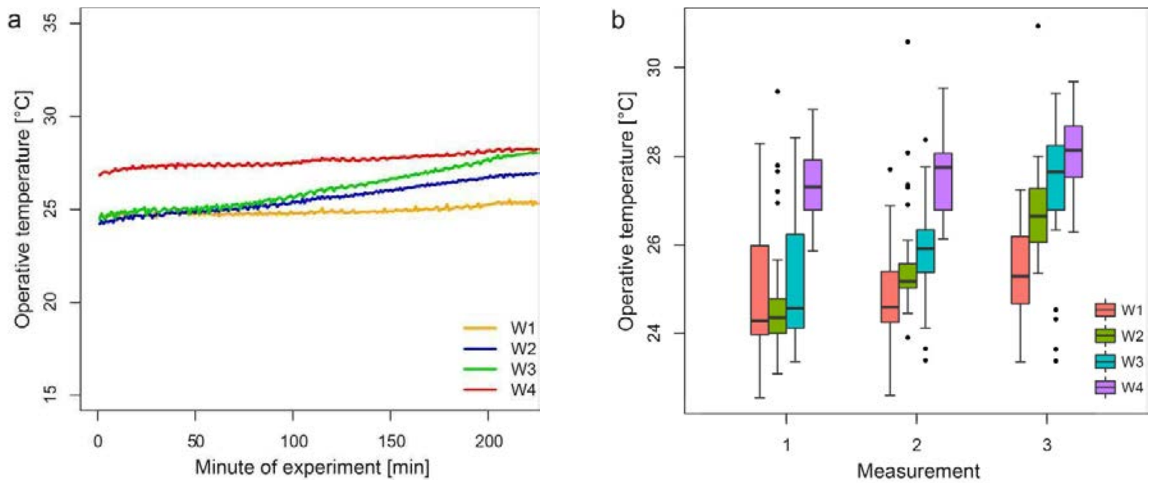

Fig. 2. (a) mean values of operative temperature measured throughout all experimental days at each minute of experiment; (b) boxplots of operative temperature at each time of measurement separated for each condition.

3.1. Subjective responses

Fig. 3 is showing the distribution of thermal sensation (TSV), thermal comfort (TCV), and thermal preference (TPV) votes at each measurement. In general, the trends represent what was expected through the thermal conditions. According to the Wilcoxon signed rank test for the TSV, the comparisons W3/3_W4/3 (mean 4.5 vs. 4.5; p=.63) and W2/3_W3/2 (mean 4.3 vs. 4.2; p=.84) did not reveal significant differences. The same applies for TCV (W3/3_W4/3: mean 1.4 vs. 1.4; p=.64 and W2/3_W3/2: mean 1.2 vs. 1.1; p=.41), TPV (W3/3_W4/3: mean 2.7 vs. 2.5; p=.44 and W2/3_W3/2: mean 2.8 vs. 2.8; p=.63), perceived control, and overall satisfaction.

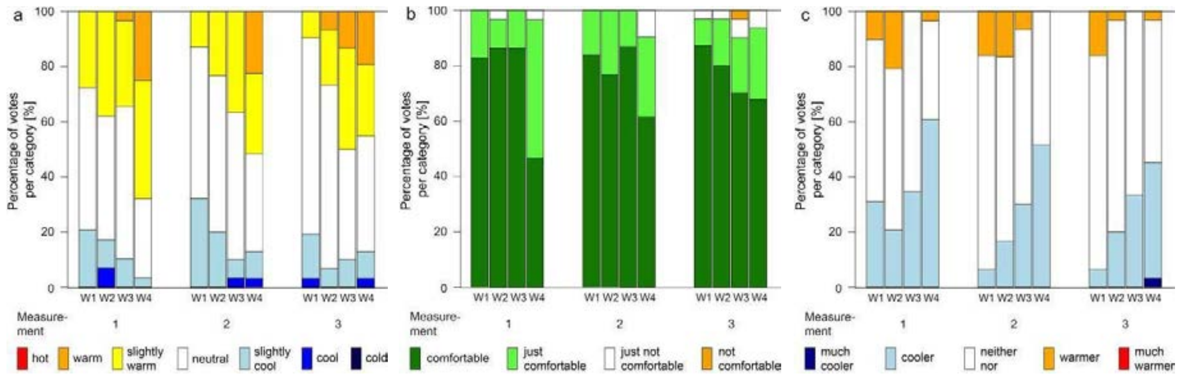

Fig. 3. Distribution of (a) TSV, (b) TCV and (c) TPV at each measurement and for each condition together with mean values for each condition and measurement (* denotes statistically significant differences between conditions).

3.2. Physiological responses

The results of the spot skin temperature measurements are shown in Fig. 4. According to the Wilcoxon signed rank test for the finger skin temperature, the comparisons W3/3_W4/3 (mean 32.5 vs. 32.5; p=.94) and W2/3_W3/2 (mean 31.6 vs. 32.3; p=.03) did reveal significant differences for the latter. It is noteworthy that at W2/3 the mean of the measured skin temperatures is lower than at W3/2 despite thermal conditions represented here by the operative temperature is higher at W2/3. As was expected, the other two spots at which skin temperature was measured were less affected by the thermal conditions, leading for arm (W3/3_W4/3: mean 33.0 vs. 33.2; p=.12 and W2/3_W3/2: mean 32.8 vs. 32.8; p=.89) and forehead skin temperature (W3/3_W4/3: mean 34.3 vs. 34.2; p=.97 and W2/3_W3/2: mean 34.0 vs. 34.0; p=.50) to negligible differences.

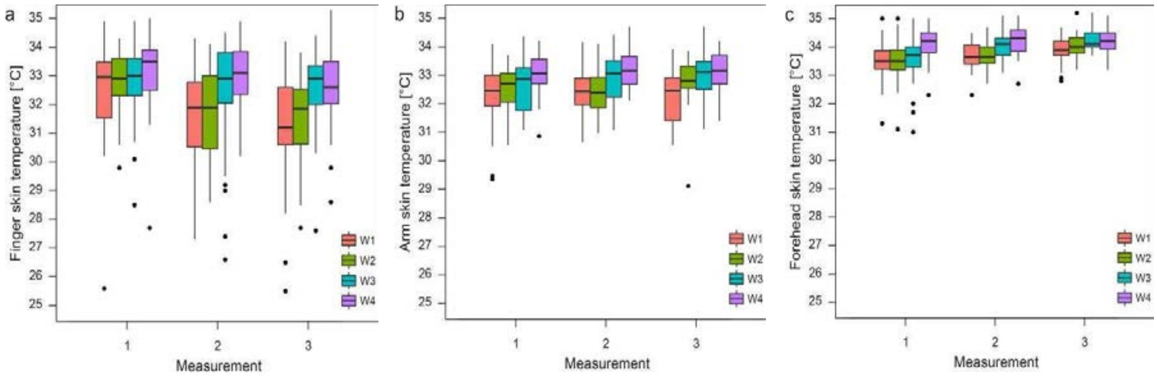

Fig. 4. Boxplots for (a) finger, (b) arm and (c) forehead skin surface temperature at each measurement and for each condition.

The results for RMSSD (Fig. 5) show tendencies towards more stressed subjects, i.e. a lower RMSSD, with higher operative temperatures. According to the Wilcoxon signed rank test, the comparisons W3/3_W4/3 (mean .12 vs. .12; p=.50) and W2/3_W3/2 (mean .14 vs. .11; p=.14) support the tendency towards more stress with a steeper ramp, but did not reveal significant differences.

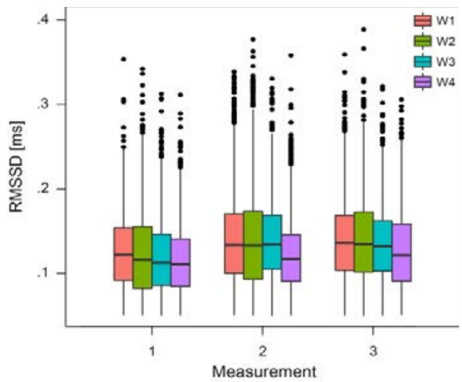

Fig. 5. Boxplots for RMSSD value around each measurement and for each condition.

3.3. Performance indicators

None of the performance indicators analyzed, i.e. the subjective productivity, the speed in the addition test, and the number of correct links in the Tsai-Partington test showed any significant difference between the sessions.

4. Discussion and conclusion

The analysis of two pairs of votes, i.e. vote 3 at session W3 with vote 3 at session W4 and vote 3 at session W2 with vote 2 at session W3, did not reveal statistically significant differences between the subjective responses. This is in particular surprising, because the operative temperatures differed statistically significant. Higher operative temperatures proceeded by a less steep ramp were thus evaluated in the same way than lower operative temperatures proceeded by a steeper ramp. This supports the hypothesis that steeper ramps lead to earlier reactions. However, the current analysis is neither able to proof nor reject this hypothesis, because – as mentioned for the forehead skin temperature – the result would also be obtained in case the response variable is not affected by the operative temperature.

As for the physiological reactions, the finger skin temperature and the RMSSD suggest that the thermoregulation system is forecasting future changes and therefore adjusting the blood flow from the core to the extremities faster for steeper ramps. Whether this causes the stress level to increase or whether the increased stress level is a reaction to the perceived changes in temperature fluctuations cannot be clarified here.

In general, these results support the hypothesis stated at the beginning, but further in depth analyses especially together with the behavioral reactions need to be done before drawing conclusions for the applicability of light-weight structures.

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